

# Personal recollections: Frascati and the search for gravitational waves at the *Istituto Nazionale di Fisica Nucleare* (INFN).

G.Pizzella  
INFN Laboratori Nazionali di Frascati  
Email:guido.pizzella@lnf.infn.it

April 25, 2016

## 1 Introduction

Along the way named Via Isacco Newton in the *Laboratori Nazionali di Frascati* (LNF) of the *Istituto Italiano di Fisica Nucleare* (INFN) in Piazza Albert Einstein one meets a building with the inscription NAUTILUS. In this building a cryogenic detector of gravitational waves is installed, the most sensitive one in the world at the end of the 90s.

NAUTILUS started to operate in 1991 and will be turned off in June 2016. I think interesting to remember briefly how it has come to carry out this research in the Frascati National Laboratories.

The story begins in 1961, when Edoardo Amaldi attended in Varenna lectures on gravitational waves by Joe Weber.

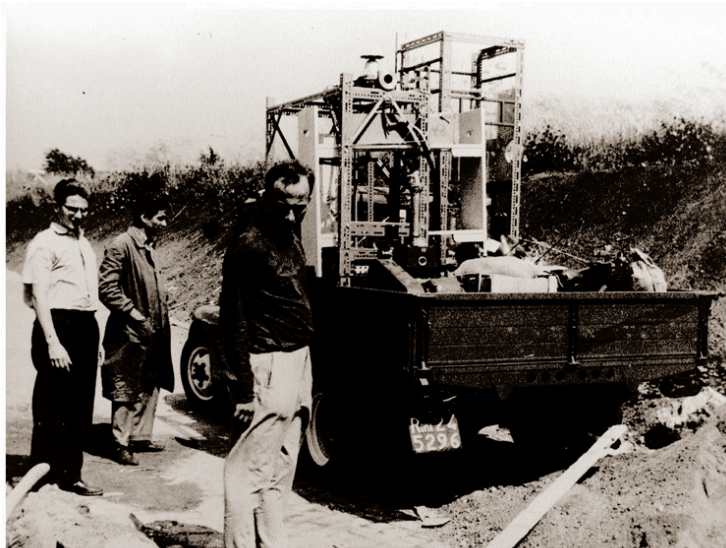
Edoardo Amaldi has been the Sower in Italian postwar physics, at least until the 70s. With great scientific acumen and aware of the responsibility that events had put him in, Amaldi launched many seeds on the soil of Italian physics. Some fell on fertile soil and, especially at the University of Rome, developed, continuing the activities initiated by Enrico Fermi with the group of via Panisperna: elementary particle physics, and then the matter, the physics of universe and gravitation. A few more attempts, however, did not catch on completely.

Amaldi had tried to convince some colleague or student to start an experimental activity in the field of General Relativity in Italy. Therefore, when in September 1970 I proposed to him to start an experiment for searching gravitational waves, he was extremely happy, gave all his support and he himself was full time in it.

The idea to start research in fundamental physics came to me during my stay at the University of Iowa (USA), where I had spent a few years doing research on cosmic rays and Van Allen radiation belts of the Earth. Being the



Figure 1: The splendid painting *The Sower* by Vincent Van Gogh well symbolizes the work of Edoardo Amaldi sower in Italian postwar physics.



1956: Trasporto del Liquefatore

Figure 2: The apparatus for the  $He^3$  in  $He^4$  diffusion experiment, built in 1955-1956 at the University of Rome. From left G. Pizzella (INFN fellowship), Franco Tesi (truck driver) and J. Reuss (German physicist) [1].

assistant of Edoardo Amaldi, during the last few years I had heard from him the importance to do experiments in the new fields of physics: gravitational waves (GW) and the infrared cosmic background. So when I told him, the next day after my return from Iowa City, that I wished to start an experiment for the search of gravitational waves, his eyes lighted and he stared at me in a way which I shall never forget.

In January 1971 Remo Ruffini<sup>1</sup>, who was then at the University of Stanford, sent to Amaldi, on a confidential basis, the proposal of William Fairbank (University of Stanford) and William Hamilton (University of Louisiana) for a large five-ton ultracryogenic antenna equipped with a SQUID transducer. Immediately I decided that also in Rome we would have to make a similar experiment. Since we needed a laboratory that could house the antenna and also served cryogenic physicists I proposed Frascati. In Frascati in 1956 I had worked in the installation of the He liquefier and I had performed diffusion experiments  $He^3$  in  $He^4$ , first Italian researcher working in Frascati with a scholarship INFN, along with J. Reuss and with the technicians Solinas and Bellatreccia, when still the only place fit for use was the laboratory for the helium liquefier (see fig.2).

Amaldi immediately summoned a meeting with the director of the INFN Laboratories in Frascati, Italo Federico Quercia, who appeared favorable to

<sup>1</sup>Remo Ruffini had just got his *laurea* degree at the University of Rome with a thesis on relativistic astrophysics.



Figure 3: EXPLORER at the SNAM-Progetti in Monterorondo. From left: Pallottino, Modena, Pizzella, Amaldi, Serrani, Carelli, Lucano, Giovanardi and, in the lowest line, a technician and Foco.

start this new activity in the LNF. The next day I went to Frascati to discuss it, but it was clear that the interest had been expressed only in words, as there were already more research to be pursued.

However we continued to develop the project, also arousing a lot of interest in theoretical physicists, as Bruno Bertotti, Nicola Cabibbo and Bruno Touschek [2]. Since the beginning we had the important collaboration of Ivo Modena and Giovanni Vittorio Pallottino<sup>2</sup>, old fellow adventurers. The experimental activity started at the laboratories of the Snam-Progetti ENI in Monterotondo, by Giorgio Careri who had been the director, for the installation and commissioning of the great detector. SNAM had set up the premises and purchased a liquefier for liquid helium. In the spring of 1974 we moved to Monterotondo where all the pieces began to arrive of the cryostat for the large antenna. I well remember that during this period we had the visit at Monterotondo of Bruno Touschek, with whom we discussed the pilot project ending finally with a toast.

In the following years the experiment went on with changing fortunes and,

---

<sup>2</sup>GianVittorio Pallottino had been an important coworker for my space experiment on the solar wind.

after leaving the SNAME-Projects and after a further attempt to go to Frascati, then unavailable for political reason, we landed in 1980 at CERN, very well received, where finally we realized the cryogenic antenna EXPLORER cooled to 2 K. This antenna has worked continuously until 2010, when the collaboration with CERN was terminated. As for funding, which until 1980 had been secured by the CNR, they were provided by the INFN.

## 2 Gravitational waves: do they exist ?

The existence of gravitational waves (GW) was predicted already in 1900 by Lorentz and independently in 1905 by Poincaré, based on a natural analogy of the Newtonian field with the Coulomb field. In 1916 Einstein showed that one of the solutions of its linearized equation of General Relativity has just the analytical form of a wave, and showed that it would have been extremely difficult the measurement due to the very low interaction with matter. Moreover Levi-Civita, co-founder along with Ricci-Curbastro of the mathematical technique by which Einstein was able to develop the GR, argued that the solution found by Einstein had physical content, being only a wave of mathematical coordinates. I came to know this fact by Edoardo Amaldi, as he told me about the exchange of letters between Einstein and Levi-Civita.

Einstein initially was convinced that the gravitational waves had a reality, but in 1936 he wrote a paper [3] with Nathan Rosen in which, essentially, he resumed the arguments of Levi-Civita. The work was rejected by Physical Review because it contained an error. However, it is interesting to remember this story because it indicates that the physical reality of the gravitational waves is not so certain, and only their experimental revelation will settle the issue.

Let us briefly recall the fundamental equation of GR

$$R_{ik} = \frac{8\pi G}{c^2}(T_{ik} - \frac{1}{2}g_{ik}T) \quad (1)$$

where  $R_{ik}$  is the Ricci tensor,  $T_{ik}$  the energy-momentum tensor, ( $T$  its trace) and  $g_{ik}$  is the metric tensor that comes also in  $R_{ik}$  in a nonlinear manner. The tensor  $g_{ik}$  is the unknown in Eq. 1 and describes the action of gravity as a deformation of the space-time geometry. Linearizing this equation, ie introducing the possibility of weak field  $g_{ik} = \mathbf{1} + h_{ik}$  with  $h_{ik} \ll \mathbf{1}$ , we get

$$\Delta h_{ik} - \frac{1}{c^2} \frac{\partial^2 h_{ik}}{\partial t^2} = 0 \quad (2)$$

in vacuum. Thus the gravitational waves travel in vacuum with the speed of light. In the following we indicate with  $h$  the amplitude of the GW.

Assuming the existence of GW, it is possible to calculate the carried power and it is found that is extremely small. Already Einstein in 1916 calculated that the power irradiated from any source achievable in a laboratory is so small that *it has a practically vanishing value*. For this reason, today only cosmic

sources, where huge masses and accelerations are available, are taken into account. Among them we list:

- The GW emitted from binary star systems. Some years ago Hulse and Taylor were awarded the Nobel Prize by measuring the decrease of energy of the binary system PSR 1913+16 and showing, among other things, that it loses energy just as required by GR.
- The GW emitted by pulsars. This can happen if the pulsar does not have spherical symmetry, so that its tensor of quadrupole varies in time due to the rotation. To give an idea of how small is the signal expected on Earth, if we consider a neutron star with radius of 10 km and with an equatorial asymmetry of  $100 \mu\text{m}$  rotating with a period of 1 ms, we find on Earth, at a distance of 1 kpc, a perturbation of the metric tensor of the order of  $h \sim 5 \cdot 10^{-27}$ .
- The GW emitted by supernovae. Also in this case it is necessary that the explosion be non symmetrical. There are many models on the way, but in general we can see that the perturbation of the metric tensor observed on Earth for a supernova in our Galaxy is of the order of  $h \sim 10^{-18}$ , depending on the model and on the distance.
- The GW emitted by the fall of a star into a black hole.
- Finally the GW generated at the Planck time, that is  $10^{-43}$  seconds after the big bang. The measurement of such GW should lead information to understanding the birth of the Universe.

### 3 The gravitational waves detectors

#### 3.1 Interferometric detectors

The arrival of GW in a region of space changes the laws of the flat Euclidean geometry, by introducing a curvature. Imagine a flat plate that, when the wave comes, becomes curved. The consequence is that the distance between two points varies; for example two points at opposite ends of the plate when this is curved approach. This is the principle on the basis of operating interferometers.

The interferometer consists of a laser light from a point that goes, through a beam splitter, in two directions perpendicular to each other, it is reflected by two mirrors placed at the same distance (3 km in the case of VIRGO) and returns to the starting point. Upon arrival the two beams are no longer in phase, as they were at the start, because one of the two beams has traveled a different distance from the other.

So far two LIGO interferometers (arms 4 km) installed in Livingstone in Louisiana and Hanford in Washington State, VIRGO (arms 3 km) installed in Cascina and GEO (arms 600 m) installed in Hannover in Germany have been from time to time in operation. The most ambitious one is certainly the LIGO project, which started a few decades ago and reached a sensitivity greater than that of the bar detectors in 2005, as shown in an exchange of letters with the former principal investigator Barry C. Barish (see fig. 4).

About VIRGO, I think it was an error by the European scientific commu-



**From:** "Barry C. Barish" <barish@ligo.caltech.edu>  
**Date:** 14 ottobre 2005 19:02:52 GMT+02:00  
**To:** Guido Pizzella <guido.pizzella@Inf.infn.it>, barish@ligo.caltech.edu  
**Subject:** Re: congratulations!

Guido

Thanks for the very kind statement, which I have shared with my colleagues. Now, we are very anxious to get a good long data run at this sensitivity (our S5 run) and perhaps we will see something!

Barry

At 01:47 AM 10/14/2005, Guido Pizzella wrote:

Dear Barry  
I have seen the sensitivity curves of LIGO.  
Congratulations!  
It seems to me that now LIGO has a sensitivity of the order of  $h(\text{adimensional}) \sim 2 \cdot 10^{-21}$  for bursts, which means that you could see supernovae in VIRGO (for an optimistic emission of gravitational waves). This is exactly my dream when I started to work in the field 35 years ago. For a bar, this limit could be reached at the quantum limit, but we are two orders of magnitude away and I doubt the quantum limit will ever be reached with resonant detectors.  
So, again congratulations to you for having been able to bring the scientific community to such high level.  
I sincerely wish you the best  
Guido Pizzella

Figure 4: Exchange of letters with the former LIGO principal investigator Barry C. Barish.

nity not to launch two interferometers instead than just one. This is because the search for such feeble signals needs the use of a two, at least, coincidence experiment (see later the section *search for coincidences*). This is what they do in USA with two LIGO and, if GW will be discovered [4], the credit shall not belong to the European Science.

### 3.2 The resonant detectors

Joe Weber of the University of Maryland had, in the 50s, a very ingenious idea. He thought that the perturbation  $h$  of the metric tensor would have put in vibration a massive bar. To get an idea of the magnitude of these vibrations you can consider the explosion of a supernova in our Galaxy (of course, rule out the chance that the explosion takes place in the vicinity of the Earth, because if this would happen, life on Earth would end). It is estimated that a galactic supernova would vibrate the bar with an amplitude of the order of  $10^{-18} m$ . This vibration is faced with the vibrations caused by the thermal noise of the bar. A bar of mass  $M = 1000$  kg cooled to the temperature of 1 K has a thermal vibrations on the order of  $10^{-17} m$ , greater than the signal we want to measure. To this noise an equal noise due to electronic devices shall be added.

From here we understand the great difficulty of the experiment that seeks signals due to GW, as the gravitational forces generating the signal compare to the much more large electromagnetic forces which produce the noise. The problem is faced by cooling the detector and using optimized filtering algorithms in order to extract small signals in the presence of a large noise.

Despite these difficulties various experimental groups in the world decided to take the road to study such a fleeting phenomenon. Some groups terminated

their activity very soon, among them a group in Canada and one in Rochester. The group at Stanford, founder of the cryogenic detectors, decided to end the experiment when, on October 17th, 1989, an earthquake badly hurt their cryogenic antenna. Five groups succeeded and began to put into operation cryogenic detectors: in 1990 EXPLORER at CERN, in 1991 ALLEGRO in Louisiana, in 1993 NIOBE in Australia, in 1994 NAUTILUS in Frascati and in 1997 AURIGA in Padua, this last one a replication of NAUTILUS.

Except for NAUTILUS and AURIGA, the operation of the resonant detectors has been terminated, because the laser detectors, though not able to reveal massive particles, are much more sensitive for the detection of gravitational waves. The last two resonant detectors NAUTILUS and AURIGA will be turned off in June 2016<sup>3</sup>

### 3.3 The EXPLORER resonant detector

The gravitational wave detector EXPLORER consists of a bar of aluminum 3 meters long, with a diameter of 60 cm and a mass of 2270 kg. Upon arrival of the gravitational wave it should vibrate at its longitudinal resonance frequency  $\nu \approx 915$  Hz, with amplitude extremely small, order of  $h$ . The vibration is detected by means of a capacitive electromechanical transducer, consisting of a capacitor, one plate of which is fixed and the other one vibrates at the same frequency of the bar, a system of two coupled oscillators. The distance between the plates varies when the bar is solicited by a GW or by noise. An electric charge is put on the capacitor and generates a signal of variable voltage when the distance between the plates varies due to the vibrations. The signal is amplified by a SQUID<sup>4</sup> and recorded.

The transducer was built in the laboratories of Frascati CNEN (hereinafter ENEA) under the direction of Roberto Habel. It is important to remember this because it shows a first important collaboration for the search of gravitational waves with a physics group in Frascati.

A fundamental step to take when a new instrument is built is its calibration. For Explorer we have used a time-varying gravitational field generated by a rotor with frequency half of the resonant frequency of the bar [11]. The measurements were in perfect agreement with the expected values and this gave us confidence in the reliability of our instrumentation.

Given the smallness of the signal expected for the GW we must take many precautions. First thermal noise must be made the smallest possible. This is done by putting the bar in a cryostat, that is in a container cooled with liquid helium (4.2 K at atmospheric pressure). The cryostat, consisting of several

---

<sup>3</sup>These detectors were supposed to be turned off at the end of 2015. Their life has been extended to cover a few months in 2016, because, during this period, the operation of the interferometers is stopped for the work needed to improve their sensitivity.

<sup>4</sup>The SQUID are superconducting devices which measure weak magnetic fluxes, in our case obtained by sending the signal from the transducer in a reel. An important use of these devices is the study of weak electrical currents generated in the biological brain circuits. It was also attempted to apply them in cybernetic circuits, so far without a complete success.



cylindrical containers each of which at a temperature decreasing towards the interior, must be as more as possible isolated from external mechanical disturbances. This is obtained by suspending the various cryogenic vessel of the cryostat by means of cables which play the role of mechanical filters and finally by suspending the bar in the most interior container with a cable that wraps partially below its gravity center section. In this way we get a good mechanical attenuation in total of approximately 200 dB, which assures the attenuation of mechanical disturbances<sup>5</sup>.

EXPLORER was the first cryogenic detector to operate continuously since the year 1990 at temperature of 2 K with good sensitivity, the greatest sensitivity until the year 2000.

## 4 Going back to the Frascati Laboratories: NAUTILUS

On December 5, 1989 suddenly Edoardo Amaldi, the Sower of the Italian Physics, passed away. A few days later, on December 18, I was in my office at the University *La Sapienza* in Rome, when I received a phone call from Enzo Iarocci (... tip in a dream by Edoardo Amaldi? ...). Enzo, who was to become director of the LNF from January 1, 1990, was proposing to bring the NAUTILUS detector under construction at CERN in the Laboratories of Frascati, where liquid helium liquefiers were available. We recall that NAUTILUS was under construction at CERN because this was the only lab available for our group, but the idea was to carry NAUTILUS in another place as soon as the construction was over, in order to be able to study events in coincidence between two detectors installed in far away places.

Soon after we met in the LNF. Iarocci showed me the building where to put the NAUTILUS. In about a year the transfer was made. Before we had taken steps to build a metal swivel where NAUTILUS would have been installed. NAUTILUS is shown in figures 5 and 6. NAUTILUS, with a bar identical to EXPLORER, has been equipped with a dilution refrigerator which allows a cooling of the bar down to 0.1 K in order to increase the sensitivity by reducing the thermal noise. This temperature was never reached so far for large bodies, so that we could say that NAUTILUS is the coldest heavy body in the Universe, unless you consider the possible existence of other intelligent beings.

## 5 Search for coincidences

The major problem in all the GW experiments is the smallness of the signals (due to the gravitational force) compared with the noise (due to electromagnetic forces). Thus we are forced to operate in conditions of very small signal-to-noise

---

<sup>5</sup>The detector moreover is sensitive to even minor earthquakes, but this is taken into account by the help of seismographs and especially by the coincidences with another detector located at a great distance.

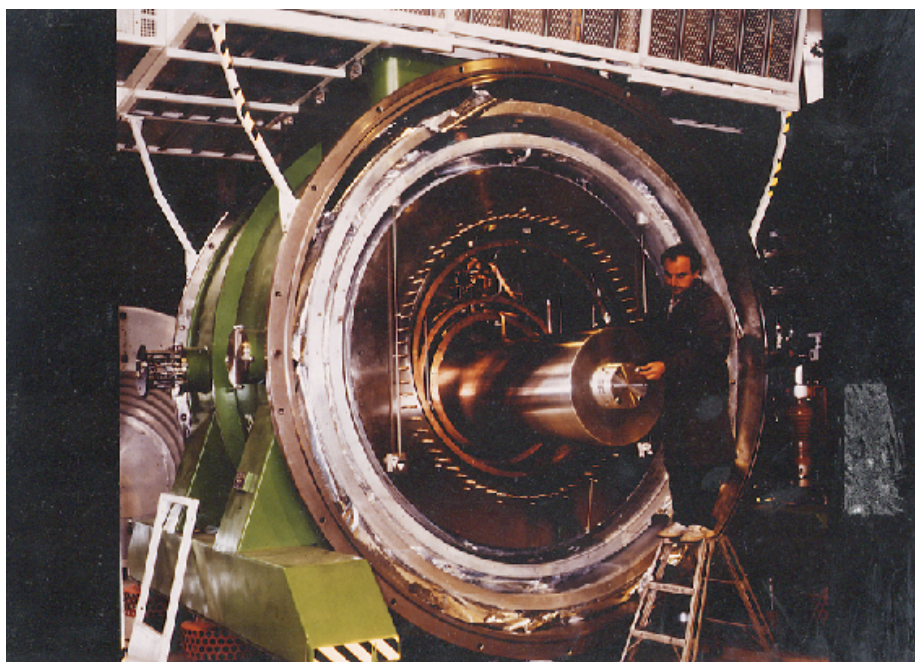


Figure 5: The GW detector NAUTILUS at the INFN Laboratories in Frascati.



Figure 6: NAUTILUS with the cosmic ray detectors.

ratios. In this situation, even in presence of well behaved noise, we must take into consideration as GW candidates a large number of data, in the very great majority due to noise but which could embed rare and precious information on possible GW. Neither is possible to reduce significantly the number of candidate data by a careful screening, using information from different instrumentation.

For example, suppose the detector has a well behaved noise expressed in unit of kelvin,  $T_{eff} = 5 \text{ mK}$  with a Maxwellian distribution, and a bandwidth of 10 Hz. In one hundred days we have  $100 \cdot 864000$  independent samples and the number of samples with energy, say,  $E > 50 \text{ mK}$  (that is  $SNR \geq 10$ ) is

$$N(E > 50 \text{ mK}) = 100 \cdot 864000 e^{-\frac{50}{5}} \sim 3900 \quad (3)$$

a large number.

In the real case, with additional noise of unknown origin, we may have a number of samples above threshold one or two orders of magnitude greater. Eliminating the data correlated with seismic signals, as done by the Rome group, the number of data reduces by only a few percent.

It is possible, however, to improve considerable the search of GW by employing the coincidence method, as initially done by Weber. For example, suppose we have two equal detectors, each detector providing 10000 candidate data (signals above a given threshold) over a period of one hundred days. With a coincidence window of 0.1 s ( $\pm 0.05 \text{ s}$ ) we have an average number of accidentals

$$\bar{n} = \frac{10^4 \cdot 10^4 \cdot 0.1 \text{ s}}{100 \cdot 86400} \sim 1 \quad (4)$$

that is, we reduce by a factor of ten thousand the candidate data to consider as possible GW.

This argument appears rather obvious:

*give most importance to the coincidence technique for cleaning the data, much more than any other technique.*

Yet many people do not give proper consideration to that. I have had several discussion with other scientists, who treat the data before searching for coincidences on the basis of theoretical expectations and do not care for another detector to compare with. As example, the VIRGO experiment, just one detector, initially designed to detect waves possibly generated by pulsar

In my opinion the analysis of data should consist essentially in comparing the signals in time coincidence among two or more detectors. In the case of coincidence search the background can be obtained, for example, by shifting several times the time of occurrence of the events of one of the detectors<sup>6</sup>.

With this experimental procedure one circumvent also the problems arising from a non stationary distribution of the events.

A different reliable approach is provided by the Bayes theory. According to this theory the probability to have a certain result depends on the degree of belief, due to previous information, and on the statistical computations with the new data.

---

<sup>6</sup>It can be shown that this experimental background determination has to be preferred to the random reshuffling procedure.

## 5.1 Search for coincidences with EXPLORER and NAUTILUS

We have applied the Bayes method for determining upper limits to the GW searched with resonant detectors. The result and the procedure has been described in ref.[6].

Using the most common procedure for the search of coincidences we have processed the data obtained with NAUTILUS in time coincidence with other operating resonant detectors, particularly EXPLORER. In the following we describe very briefly some results.

The most interesting one has been obtained with data recorded during 1998 in the period 7-17 September when an intense activity of the black hole candidate XTE J1550-564, and within days of the giant flare from the magnetar SGR1900+14 occurred. During this period we had 21 coincidences ( $\pm 0.5$  s) between signals recorded by the two detectors, while expecting on average only 8.1 due to chance. Furthermore there was also a significant correlation between the coincidences and the onset of the X-ray emissions [7]. One coincidence was due to the largest events ever found, in coincidence, in all our experiments, 5.7K for EXPLORER and 5.8K for NAUTILUS. It is unfortunate that no other GW detectors was in good operation during 1998. In my opinion, we missed the best opportunity for an important discovery. In the rest of the year 1998 over a total period of 95 days we found 61 coincidences while expecting by chance 50 [8].

Other intriguing results were obtained in the year 2001 with data collected by EXPLORER and NAUTILUS, for a total measuring time of 90 days [9]. We repeated the coincidence search as with the 1998 data, using the same algorithms based on known physical characteristics of the detectors. An interesting feature was found during the sidereal hours in the range 2-5, when the detectors were favorably oriented with respect to the Galactic Disk. We found 8 coincidences while expecting, by chance, 3.1.

Similar result was also obtained with data recorded during 2003. In the range 2-5 sidereal hours we found 6 coincidences while expecting, by chance, 1.6.

Such coincidence excesses were not found after the year 2003.

It is evident that these results, although intriguing, are not sufficient to make any claim, taking also into account that no other GW detector supported them. The real problem with the resonant detectors is their poor sensitivity, unless we believe that cooperative mechanisms are operating during the interaction of GW with the detectors, as suggested by Giuliano Preparata [10].

## 5.2 Signals from cosmic rays

Contrary to the interferometric detectors, the resonant detectors are sensitive to the passage of particles. We have used this feature especially to perform a sort of *absolute* calibration of the bar-detector, measuring the relationship between the bar signal and the energy deposited in the bar, therefore we are sure that the tiny signals seen by the detector, extracted by means of optimized algorithms,

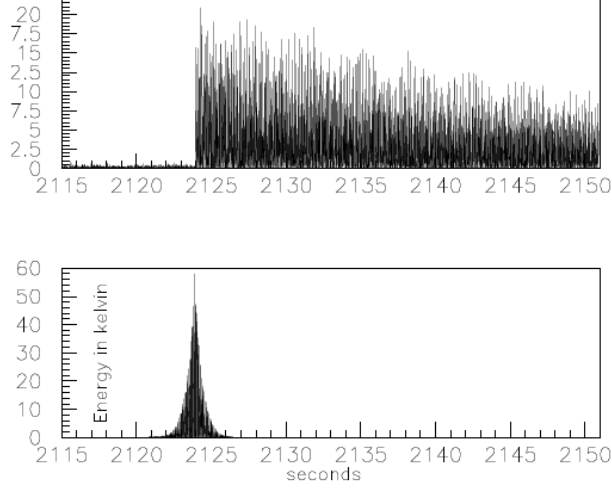


Figure 7: The signal (volt square) before optimum filtering versus the UT. The time is expressed in seconds, from the preceding midnight. From the decay we evaluate the merit factor of the apparatus,  $Q = 1.7 \cdot 10^5$ . The lower figure shows the data after filtering, in unit of kelvin. Here the reverse of the decay time gives the detector bandwidth equal to 0.34 Hz .

correspond to definite amounts of released energy. No other GW experiment has done it, and the usually adopted calibration procedure requires a modeling of the calibration apparatus.

The signals are due to the mechanical vibrations produced by the expansion that has along the path of the particles because of the warming for to energy dissipation. Therefore the signals depend on the ratio of the thermal expansion coefficient to the specific heat, that is the Grüneisen. coefficient. This is independent of temperature at least until the material becomes superconducting (1 K for aluminum). The various acoustic models give the energy  $\epsilon$  expected in resonant mode detectors

$$\epsilon = 7.64 \cdot 10^{-9} W^2 \cdot f \quad (5)$$

where  $\epsilon$  is expressed in kelvin,  $W$  (in GeV) is the energy dissipated in the bar, and  $f$  is a geometric factor of the order of unity.

Measurements were performed with NAUTILUS and EXPLORER using equipment for cosmic rays designed and built by Francesco Ronga. One of the results [12] is shown in Figure 7 where a very large signal due to a cosmic ray shower is reported.

We also found signals larger than calculated with Eq. 5 when the detector was cooled to 0.1 K,.

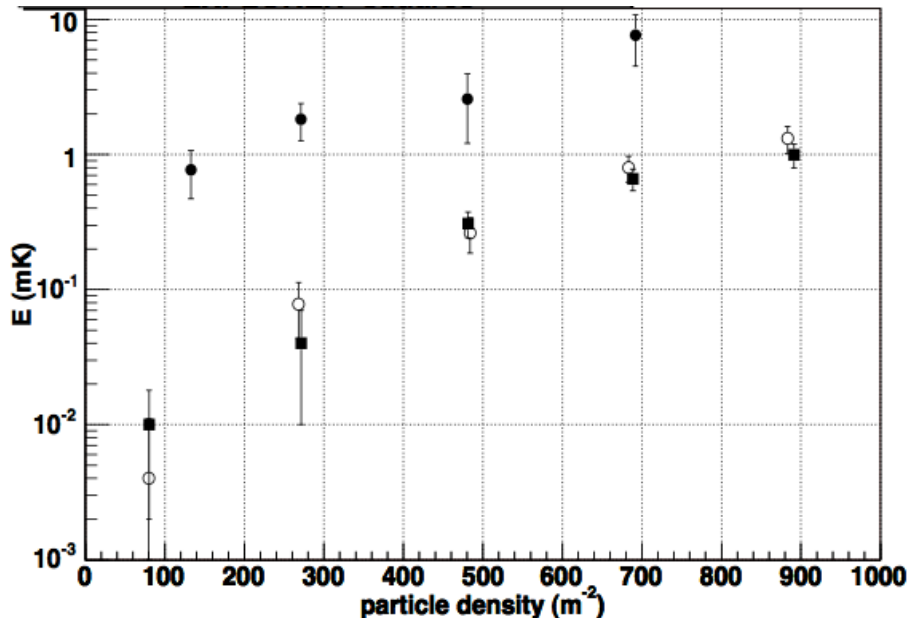


Figure 8: Filled circles NAUTILUS at  $T = 0.14$  K, open circles NAUTILUS at  $T = 3$  K, Filled squares EXPLORER at  $T = 3$  K. The data gathered at  $T = 0.14$  K are roughly one order of magnitude larger than those collected at  $T = 3$  K.

In order to obtain experimentally the relationship between the energy of the particles interacting with the detector and the generated signal, we performed an experiment, called RAP at the INFN Laboratories using a small aluminum rod cooled to 0.1 kelvin and subjected to the electron beam from DAPHNE.

The result [13] is shown in Fig. 8. We found an increase of about one order of magnitude in the energy of the signals, due to the superconducting state of the aluminum.

As a by-product NAUTILUS has led interesting contributions in setting upper limits on exotic components of cosmic radiation [14]. This search has been carried out using data from NAUTILUS and EXPLORER equipped with cosmic ray shower detectors. We remark that the particle detection mechanism is completely different and more straightforward than in other cosmic ray detectors. The results of ten years of data from NAUTILUS (2003-2012) and 7 years from EXPLORER (2003-2009), searching nuclearites of mass less than  $10^{-4}$  gram, show a flux smaller than predicted considering nuclearites as dark matter candidates.



## 6 Final consideration

As recognized also by members of the American NSF, as shown in fig.9, the search for gravitational waves carried out by the Rome group<sup>7</sup> played an important role in the scientific landscape. The international scientific community has given the name *Edoardo Amaldi* to the most important Conference, repeated every two years in different countries, for the search for gravitational waves.

Although the discovery of gravitational waves has remained a mirage for us, I believe we have brought contributions to the development of this research, culminating in the large interferometers [4], and in the space experiment LISA, full of hope, which soon will tell us whether the mirage reflects a new reality.

Everything was made possible by the vision of Edoardo Amaldi, both for his contribution to the creation of the National Laboratories of Frascati and CERN, both for his open to any new scientific enterprise. To this day it is unlikely to find such Builders of Science. The succession of life leads to the Big Science with thousands of researchers who trooped, and hardly they can see other possible horizons.

An exception to this general trend when accidentally found myself in September 2009 alongside Marcello Piccolo, during a fifty-year marriage celebration of our common friend Lina Barbaro Galtieri. I proposed to Marcello a new experiment, to be carried out in Frascati, for the measurement of the propagation of the Coulomb electric fields. The idea of this experiment had come by considerations on the physics of systems of reference and therefore I regard it a natural consequence of research in the field of General Relativity.

Marcello, while engaged in other experiments, agreed. The experiment, which aroused also the interest of Giorgio Salvini<sup>8</sup>, gave the result described in the paper [15]. With this experiment we found that a moving electric charge carries **rigidly** its own Coulomb field. The scientific significance of this result has not yet been evaluated in full.

We are now trying to repeat this experiment at the Frascati National Laboratories (sixty years after my first experiment here) or elsewhere. Despite some of my previous considerations, I remain very optimistic about the future of Science.

---

<sup>7</sup>Over the years the activities carried on by the Rome group of gravitational waves relied on contributions from several researchers listed here: Edoardo Amaldi, Pia Astone, Danilo Babusci, Massimo Bassan, Romano Bizzarri, Paolo Bonifazi, Franco Bordoni, Pasquale Carelli, Gabriella Castellano, Giorgio Cavallari, Eugenio Coccia, Carlo Cosmelli, Sabrina D'Antonio, Antonio Degasperis, Viviana Fafone, Valeria Ferrari, Sergio Frasca, Franco Fuligni, Gianfranco Giordano, Umberto Giovanardi, Roberto Habel, Valerio Iafolla, Ettore Majorana, Alessandro Marini, Evan Mauceli, Yuri Minenkov, Ivo Modena, Giuseppina Modestino, Arturo Moleti, GianPaolo Murtas, Yujiro.Ogawa, Gianvittorio Pallottine, Guido Pizzella, Lina Quintieri, Piero Rapagnani, Fulvio Ricci Alessio Rocchi, Francesco Ronga, Roberto Terenzi, Guido Torrioli, Massimo Visco, Lucia Votano. It has been their dedication to this difficult experiment that allowed the group to position itself at the forefront in the world of search for gravitational waves.

<sup>8</sup>Salvini [1921-2015] had been the first director of the Frascati National Laboratories.

## 7 ACKNOWLEDGMENT

I thank my wife Elena for her continued encouragement. This paper is part of an activity aimed to give a contribution to the history of the INFN Frascati National Laboratory. I am grateful in particular to Lia Pancheri, for asking me to give a memory about the search of gravitational waves at LNF. I thank also Giorgio Capon, Giovanni Vittorio Pallottino and Francesco Ronga for useful discussions and suggestions.

## References

- [1] <http://www.lnf.infn.it/lnfimages/> , area: historical , liquefattore
- [2] Bruno Toushek had a very important role in the experiments performed at LNF, with great impact on Physics all over the world.
  - a) E. Amaldi. 1981, The Bruno Toushek Legacy, CERN 81-19, available at <http://cdsweb.cern.ch/record/135949/files/CERN-81-19.pdf>
  - b) Luisa Bonolis, Giulia Pancheri, *Bruno Toushek: Particle physicist and father of the e+e collider*, Eur.Phys.J. H36 (2011) 1 e-Print: arXiv:1103.2727.
- [3] *Controversies in the history of the radiation reaction problem in general relativity*  
Daniel Kennefick. Apr 1997. 33 pp. e-Print: gr-qc/9704002 — PDF
- [4] Recently there have been rumors that the two LIGO have detected one signal satisfying the requirements to be due to gravitational waves.  
Nature, 30 September 2015.
- [5] J. Weber, Phys. Rev. Lett. 22, 1320 (1969)
- [6] *On upper limits for gravitational radiation* , P. Astone , G. Pizzella , Astropart.Phys. 16 (2002) 441-450
- [7] a) *Coincidences between the gravitational wave detectors EXPLORER and NAUTILUS in 1998, during the activities of the black hole candidate XTE J1550-564 and the magnetar SGR1900+14* I. Modena, G. Pizzella, Int.J.Mod.Phys. D15 (2006) 485-491  
b) *Studying the coincidence excess between EXPLORER and NAUTILUS during 1998* , D. Babusci, G. Cavallari, G. Giordano, I. Modena, G. Modestino, A. Moleti, G. Pizzella May 2005, arXiv:astro-ph/0505600.
- [8] P. Astone et al., *Study of coincidences between resonant gravitational wave detectors* Class.Quant.Grav. 18 (2001) 243-252
- [9] *Study of the coincidences between the gravitational wave detectors EXPLORER and NAUTILUS in 2001* P. Astone et al. Class.Quant.Grav.19:5449-5463,2002

- [10] G.Preparata, Modern Physics Lett. A, 5 (1), 1-5, (1990)
- [11] Astone P. et al., *Evaluation and preliminary measurement of the interaction of a dynamical gravitational near field with a cryogenic gravitational wave antenna* , Zeit. Script C - Particles and Fields 50, 21-29 (1991)
- [12] *Energetic cosmic rays observed by the resonant gravitational wave detector NAUTILUS*  
P. Astone et al.. Sep 2000. 8 pp. Published in Phys.Lett. B499 (2001) 16-22
- [13] *Vibrational excitation induced by electron beam and cosmic rays in normal and superconductive aluminum bars*, M. Bassan et al.. Nucl. Instrum. Meth. A659 (2011) 289-298.
- [14] *Quark nuggets search using 2350 Kg gravitational waves aluminum bar detectors* P. Astone et al.. Jun 21, 2013. Conference: C13-07-02 Proceedings  
e-Print: arXiv:1306.5164 [astro-ph.HE] — PDF
- [15] *Measuring propagation speed of Coulomb fields* , R. de Sangro et al., Published on Eur. Phys. J. C (2015) 75: 137.

NATIONAL SCIENCE FOUNDATION  
WASHINGTON DC 20550

September 3, 1982

Professor Guido Pizzella  
G23-Istituto di Fisica dell'Universita  
Piazzale Aldo Moro, 2  
Roma 00185  
Italy

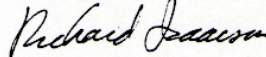
Dear Professor Pizzella:

I would like to take this opportunity to express my gratitude for your hospitality and kindness in showing me the Italian gravitational research facilities in Rome, Frascati, and Geneva. Although this was my first visit, of course I have closely followed the progress of your group as reported at conferences and in the literature. Nevertheless, I was still enormously impressed with the research already under way in Rome, as well as with the potential of the new installation at CERN.

As you know, my responsibilities at NSF require me to be aware of current trends and new developments in gravitational physics. Consequently, I have had frequent opportunities to visit all of the U.S. experimental gravity facilities. The Italian bar-receiver development program compares very favorably with the state-of-the-art here! In size, your group seems to have about as many people as the entire U.S. bar-detector effort (which is spread across Stanford, LSU, Maryland and Rochester). The quality of your general purpose laboratory equipment, computers, and electronics seemed at least as good as what I have seen in the U.S.. I found your group particularly impressive in involvement with significant technological developments likely to be crucial during the coming decade (D.C.- SQUIDS, cryogenics, parametric transducers, etc.) and for its solid engineering philosophy in the design of the overall system and its components.

Based upon my visit, it seems clear to me that your low temperature bar-detector is likely to be among the very best resonant receivers in the world. I look forward to seeing it in operation soon, carrying out large baseline coincidence experiments with U.S. groups. If I can ever be of any assistance in bringing this about, please contact me and I will certainly work hard at helping out.

Best regards,



Richard Isaacson

Figure 9: Letter by Isaacson in 1982. This marks the date when the project LIGO has received a boost.



Figure 10: Edoardo Amaldi and Guido Pizzella at the General Relativity Conference in Padua in 1983. Photo shot by Emilio Segre.